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The goals of this research program are to understand the nature and causes of acoustic signal fluctuations in the shallow water environment (i.e. the physical mechanisms). Under the auspices of this grant we have refined a three-dimensional computational acoustic modeling tool, have used computations and theories to make predictions of fluctuating acoustic behavior in shallow water, and have compared data from three field programs with the computations and theories. Research findings have been published in reports, journal articles, and conference proceedings papers.

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Ocean Acoustic Propagation: Fluctuations and Coherence in Dynamically Active Shallow-Water Regions

Final Report for ONR Grant # N00014-05-1-0482

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ABSTRACT

The goals of this research program are to understand the nature and causes of acoustic signal fluctuations in the shallow water environment (i.e. the physical mechanisms). Under the auspices of this grant we have refined a three-dimensional computational acoustic modeling tool, have used computations and theories to make predictions of fluctuating acoustic behavior in shallow water, and have compared data from three field programs with the computations and theories. Research findings have been published in reports, journal articles, and conference proceedings papers.

APPROACH

To fulfill the objective of understanding and quantifying shallow-water acoustic conditions we have applied computational models and theories to oceanographic situations encountered in three ONR-sponsored field programs. These were

1. The Littoral Environmental Acoustics Research portion of the ONR Shallow-Water 2006 experiment (SW06-LEAR), which was east of New Jersey on the continental shelf [Tang *et al.*, 2007].
2. The spring 2007 ONR/Taiwan NLIWI acoustics experiment in the ASIAEX-experiment area of the South China Sea east of Hong Kong [Reeder *et al.*, 2008].
3. The ONR Quantifying, Predicting and Exploiting Uncertainty experiment (QPE) in the East China Sea in Sept. 2009. The particular focus has been on fully three-dimensional (3D) acoustic propagation effects arising from 3D aspects of the environment. The experiments provided data in the frequency range from 100 to 400 Hz. This project has concentrated on theory and simulation at those frequencies, with the publications reporting results mostly in that band, but many of the findings are relevant over a larger band.

Internal tides and nonlinear mode-one internal gravity waves are known to often dominate acoustic variability in these (and other) regimes. For this reason the acoustic effect of internal waves is the main subject of our research. Internal waves at the location of a sound source will modulate acoustic mode excitation, and thus modulate the effects of mode-stripping on long propagation paths. The presence of short nonlinear waves along a sound propagation path can cause mode coupling (also altering mode-stripping effects) and mode refraction. Long internal waves (having wavelengths tens of kilometers), including internal tides, can alter mode shapes and mode stripping, and can alter source excitation, but have negligible mode coupling effects.

Work under this grant was aimed primarily at summer conditions in the temperate ocean (an approximate two-layer system), including work on conditions found just inshore of shelfbreak fronts. The SW06 area of the Mid-Atlantic Bight has warm water offshore and winter-cooled water on the shelf. In this particular frontal zone there can be a thin deep warm salty layer, capped by an inverted thermocline, on the near-edge section of the shelf. This area has prevalent internal waves on a shallow thermocline in the summertime, and occasional internal waves on a deep thermocline (above the thin deep salty layer) both summer and winter. The South China Sea experiment area has multiple types of large nonlinear internal waves. These are transbasin internal waves arriving from the Luzon Strait area a few hundred kilometers to the east, scattered secondary waves arising from the interaction of the transbasin waves with the continental slope, and locally generated waves forming from a steepening internal tide. Many effects on sound of these types of waves have been addressed in the publications.

The basic physics of sound propagation within ocean volumes with highly variable sound speed is well known (reflection, refraction, diffraction). However, the relevant sound-speed variations take numerous complex time-evolving forms in the three areas we have studied under this grant (and also in other areas), causing complicated propagation and interference effects of unlimited variety. To better investigate horizontal refraction we have, moved strongly under this grant into 3D parabolic equation (PE) computational acoustic modeling. This tool has allowed good progress in characterizing scattered sound features in our target environments.

ACCOMPLISHMENTS

During the course of the grant many papers or reports were published on SW06 (8), conditions in the NLIWI area (3), and QPE (1). Additionally, 12 other papers not strictly associated with these three experiments were published, for a total of 24 papers.

SW06-LEAR: A large number of pulses transmitted from moored sources to the WHOI L-array (co-located HLA/VLA) have been analyzed. Figure 1 shows the experimental arrangement. The acoustic experiment involved half-hourly sound transmissions for about three weeks.

The primary acoustic analysis has been of spatial coherence of sound fields from the 100-Hz to 400-Hz moored sources measured with the HLA. An analysis method using VLA data to diagnose the causes of spatially decorrelation was developed and used in interpret the coherence (correlation) findings (i.e. a joint HLA-VLA analysis method). Three figures depict some fundamental results. Figure 2 shows time-window average coherence length results, obtained with a broadband analysis method for HLA signals after array shape correction and beam steering for three sources. Figure 3 shows a short time series of instantaneous coherence length estimates and other parameters for one source. It is evident that the sound arrival angle is altered and coherence length is diminished by the presence of internal waves between the source and receiver. Also, the coherence length at fixed steering angle fluctuates greatly because of sound refraction and waveform interference. A manuscript describing the one-month time series of observations along the two paths was submitted to the Journal of the Acoustical Society of America at end of the grant, building on our published paper [Collis *et al.*, 2008].

Another paper covered propagation down an internal wave duct that fades (in the along-crest direction) into ambient thermocline conditions, a situation observed a few times in SW06 [Lin *et al.*, 2009]. The results show that a highly time-dependent mix of acoustic mode beams can emerge from the duct, with the beams of each mode appearing to be independent, or at least weakly coupled. Figure 4, from the paper, shows this complex sound field behavior, believed to occur for the NE to HVLA path (see Figure 1). The results are obtained with the 3D PE model. The situation is intermittent: When the source is momentarily between passing internal waves the sound is ducted as shown. A snapshot of beams is shown for each of three acoustic modes. The time behavior was examined with 4D (time-stepped 3D) computations.

A manuscript on the general topic of propagation through curves internal waves was also published [Lynch *et al.*, 2010]. That paper draws heavily on information from the SW06 experiment (internal wave shapes, ducting parameters, etc.)

NLIWI: Further 4D PE modeling was applied to the 2007 South China Sea experiment. The experiment featured sound transmitted from a fixed source to vertical arrays 3 and 6 km away, aligned so that received sound traveled along the crests of slightly curving internal waves. Figure 5 shows beams of sound predicted to occur, with computations made using environmental situations fully consistent with the large and detailed environmental data set. The simulations fully mimic the propagation along the curved waves. The simulations provide results at many angles besides those measured in the field, so other effects may be discovered. A paper on this work was submitted to t he Journal of the Acoustical Society of America at the close of the grant. The paper reports mode refractive indices and critical angles of the internal waves present during the experiment. The good comparison between the experiment and the initial model output suggests that behavior at source-receiver geometries other than that of the experiment (down the internal wave duct) can be examined. A new effect was recognized near the close of the project: strong surface ducting of sound in the large displacement internal waves, with surface ducted sound traveling in different directions than deep ducted sound. Also, the internal waves may behave like prisms, separating modes.

As part of this study, an expression for determining an "acoustically significant" nonlinear internal wave was developed. For a given refraction angle of interest, which determines "significance", the expression sets a required minimum product of wave amplitude (normalized by water depth) and upper/lower layer sound speed difference (normalized by the lower layer sound speed).

QPE: More coastal data have recently been obtained from QPE PI's. One report has been written and presentations were made at one project meeting and one US AGU Ocean Sciences Meeting. The internal wave conditions and seafloor bathymetry conditions are somewhat different from those at the other two experiment locations. One paper about focusing of sound within one canyon, possibly observed using a research vessel as a sound source, was written at the close of the grant, for submission to the Journal of the Acoustical Society of America.

3D PE Code: The Cartesian three-dimensional parabolic equation numerical code has been made available to a few ocean acoustic researchers who have requested it.

Publications Developed Fully or Partially Under this Grant

Not Experiment Specific

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QPE

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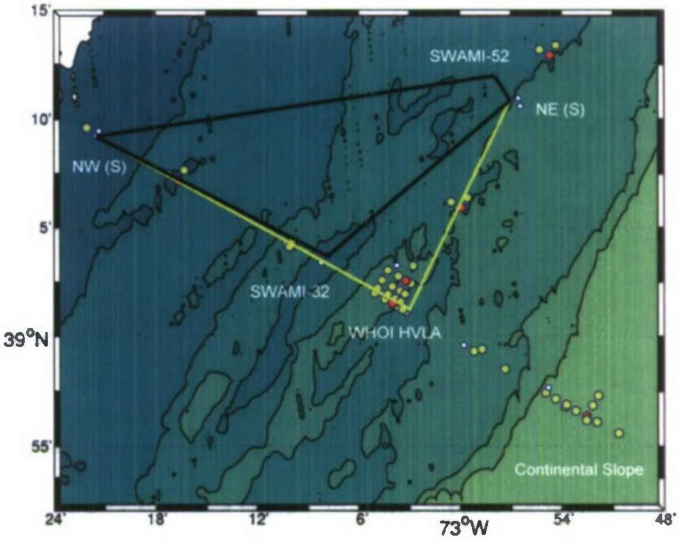

Figure 1. A chart of the SW06 experiment area east of New Jersey is shown. Pulses propagated from 224- and 400-Hz moored sources at NW and received at the WHOI horizontal-vertical line array were analyzed. Also analyzed were 100 and 200-Hz moored source pulses, also received at WHOI-HVLA. The path lengths are approximately 20 and 30 km. Depth contours of 50 to 100 m (by 10) are shown.

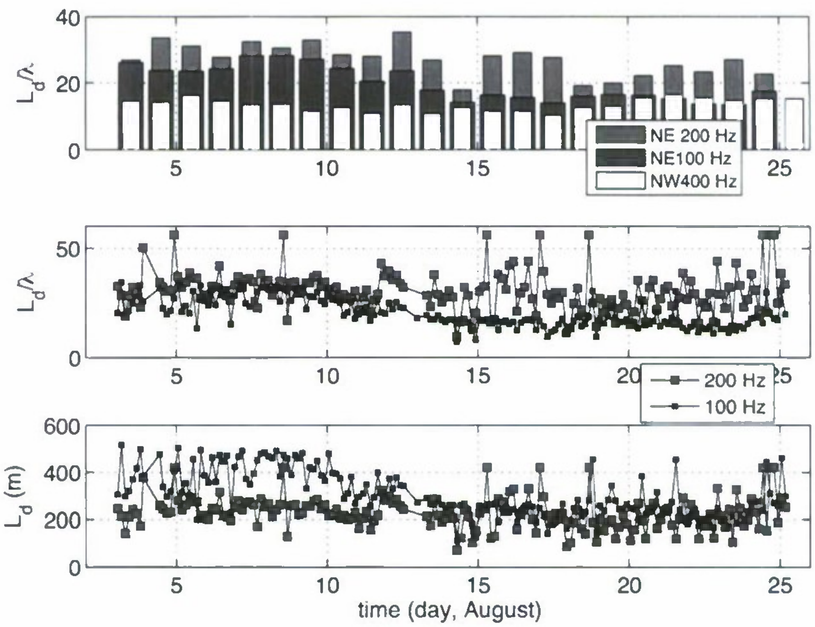

Figure 2. Horizontal coherence length estimates from NW and NE sound-source pulses received at the WHOI-HVLA in SW06 (see Figure 1). Maximum (over steering angle) coherence length estimates (L_d) are shown for 100-Hz and 200-Hz NE data and 400-Hz NW data. Two types of time averages are used to compute correlation functions (functions of horizontal distance) as a function of horizontal line array steering angle, from which L_d are computed, of which the maximum is plotted. (a) 24-hour averaging is used, with daily L_d resulting, plotted in nondimensional form using the acoustic wavelength. (b) For NE sources, the same quantities as in (a) are shown, although with 3-hour averaging is used (c) The NE-source maximum L_d values shown in (b) are plotted in dimensional form.

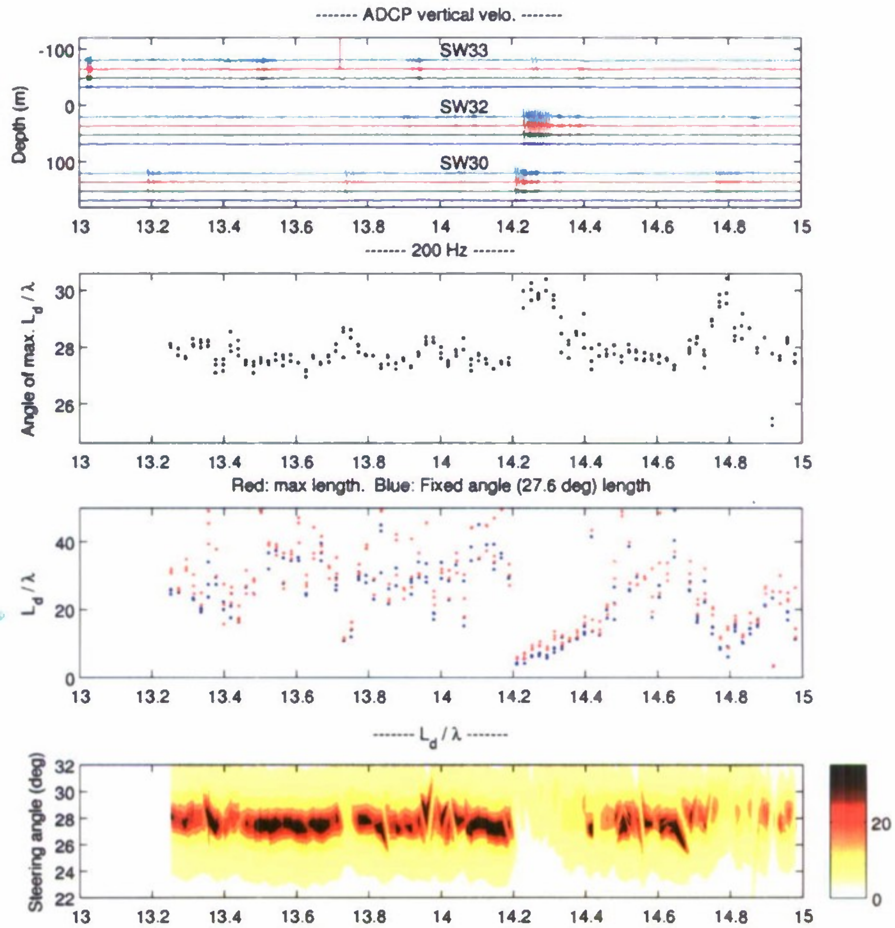

Figure 3. NE 200 Hz pulse properties and environmental properties are plotted versus time for August 13 and 14, 2006. The top shows vertical velocities at (from top) mooring SW33 (the red dot near the top of Figure 1), mooring SW32 (the red dot between NE and the receiver), and SW30 (the red dot near the HVLA receiver. The high readings indicate nonlinear internal waves with large rapid thermocline displacements. The lowest panel shows contours of 200-Hz pulse horizontal coherence length (1/e value for normalized spatially-lagged cross-correlation function), as a function of time and steering angle. The panel above that shows the maximum (w.r.t. angle) correlation length as a function of time, and the correlation length in the direction toward the fixed source. Above that, the direction of the maximum correlation length is shown. Correlation length drops rapidly and the apparent arrival angle of sound changes sharply as waves pass.

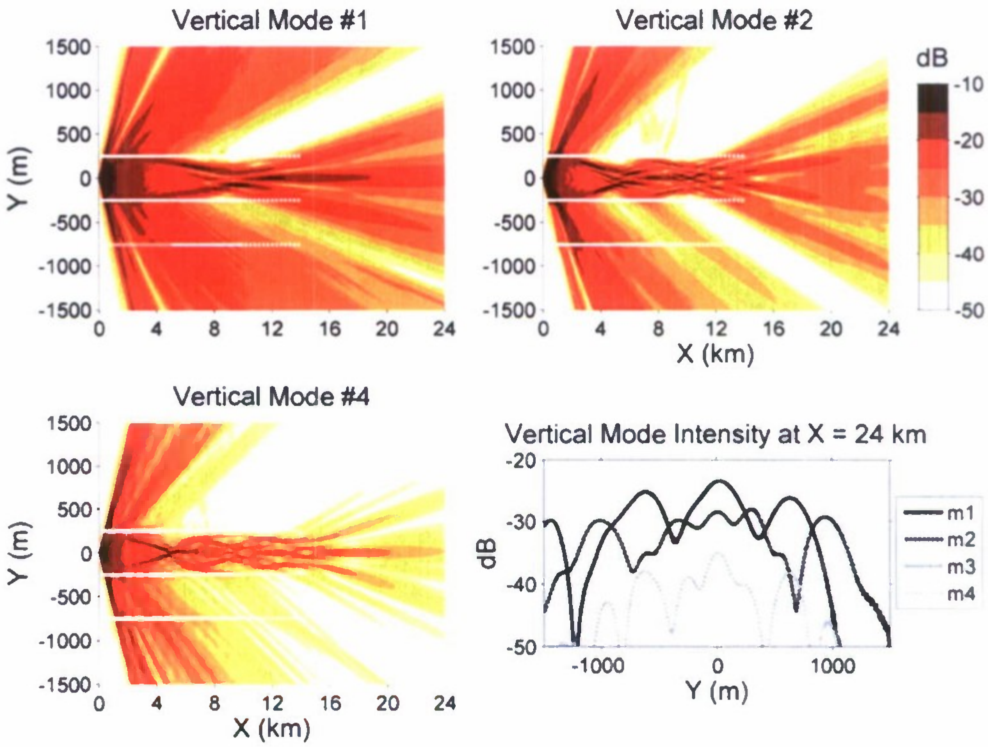

Figure 4. A snapshot of 4D simulations of sound emerging from an internal wave duct that terminates. This environmental situation was observed in SW06, with internal wave packets moving northwest and passing over source area NE were observed to flatten and disappear to the south, so that they were not present at WHOI-HVLA (Figure 1). For the depicted situation of the source in a duct, the ducted sound emerges with a different pattern for each normal mode, explaining observed SW06 behavior of unusual mode content, "missing modes", and mode multipath not consistent with propagation in simpler environments. (Figure 6 of *Lin et al.*, 2009).

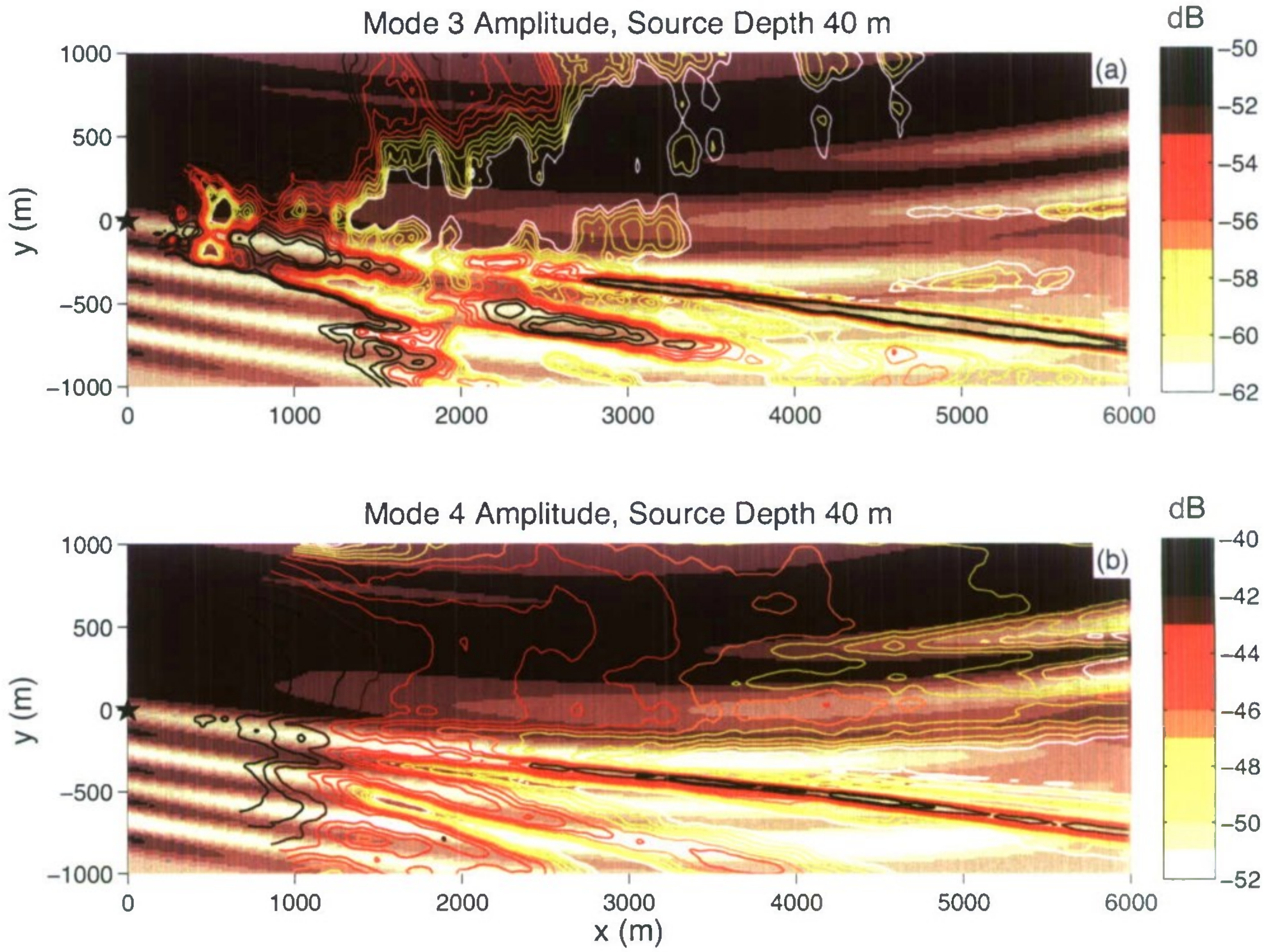

Figure 5. Two plots of 3D 400-Hz sound fields propagating through curved internal waves constructed from 2007 South China Sea NLIWI data. One time snapshot of 4D modeling is shown. The 3D fields are decomposed into normal mode constituents throughout the rectangular domain, with amplitude of mode 3 shown above and of mode 4 below with color contours. Sound is from a source at 40-m depth, which moves in and out of the warm upper layer as the waves pass. The light-to-dark color fill shows the thermocline heights in the internal waves, with dark showing depression and light showing elevation. Elevated zones are full-depth sound ducts (deep ducts, essentially) and the depressed zones are surface ducts. High mode-4 amplitude in the depression zone is a signature of enhances surface ducting. The sound source SI is at the origin. This is one of the most recent applications of Cartesian 3D-PE code in time-step mode (4D modeling).